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A Final Report on

The Structure of Turbulence and Other Motions Beneath an Air-Water Interface

by

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&

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Abstract

This is the final technical report for Grant N00014-91-J-1200, entitled "The Structure of Turbulence and Other Motions Beneath an Air-Water Interface." The grant period was from 1 November 1990 through 31 January 1994. This research couples definitive physical experiments and numerical simulation experiments to study three-dimensional, unsteady, real-fluid flows beneath the air-water interface. The overall goals for the long term are to develop (1) a complete understanding of the flow physics and (2) a numerical simulation tool that allows *accurate prediction* of the motion from a specified set of initial and boundary conditions. This report covers the early period of the long term project. The numerical tool developed is for the simulation of free-surface flows through the solution of the time-dependent, incompressible, Navier-Stokes equations with non-linear dynamic and kinematic boundary conditions. It is being developed in three dimensions; the two-dimensional version is operational. The physical experiments have focused on developing accurate maps of the flow fields under the waves with and without a surface piercing body. We have assembled a new hybrid DPIV system and analysis approach in which the correlation technique of DPIV is used as a seed for particle tracking. This produces a dense and accurate velocity field. Work on both the numerical and physical experiments is ongoing.

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1. INTRODUCTION

This is the final technical report for Grant N00014-91-J-1200, entitled "The Structure of Turbulence and Other Motions Beneath an Air-Water Interface." The grant period was from 1 November 1990 through 31 January 1994. We began in 1990 with a set of goals, defined in terms of five year milestones and ten year objectives, and a set of short-term tactical objectives. This final report, occasioned by the end of one grant and the beginning of another, chronicles the state of play in this project as of the end of January 1994.

This research couples definitive physical experiments and numerical simulation experiments to study three-dimensional, unsteady, real-fluid flows beneath the air-water interface. This zone has complex and important flow regimes and its motions are neither fully understood nor predictable. The overall goals are to develop (1) a complete understanding of the flow physics and (2) a numerical simulation tool that allows *accurate prediction* of the motion from a specified set of initial and boundary conditions.

In the following sections on these thrusts, we describe the specific developments of computational and experimental tools that we have and are making. Two thoughts drive this approach: (1) numerical codes capable of predicting wavy flows such as those found at the air-sea interface are of obvious utility, and (2) these codes will be of only limited use if the fundamental physics they model is obscure.

Given that neither numerics or experiment alone suffices to clarify the complex physical processes operant in wavy turbulent and sheared flows, it seems quite reasonable to proceed by using both in combination. Thus, we have linked the two thrusts so that they support each other, viz., in the search for new insights to the physics as numerical and physical experiments are interpreted in the context of each other, in the important validation of the numerical simulations by testing against experimental data, and finally in the guidance of experimental measurement by insight from focused numerical simulations.

2. NUMERICAL EXPERIMENTS

Our long-term objective is to be able to accurately simulate the interaction of wind, waves, vorticity, and turbulence at the ocean's free surface; including the effects of surface tension, surface contaminants, breaking waves, and submerged or surface-piercing bodies. Our grounding premise in the code development is that we must not inherently limit the potential for future expansion through choices made for the solution algorithm. Although we cannot simulate the entire physics of the ocean surface at this time, we have designed the code so that we can continue to build on it until we reach our long-term goals.

Before starting code development, we took an in-depth look at the applicability of spectral methods and did some preliminary experimentation. The results convinced us that spectral methods are not suitable for this project. Non-periodic boundary conditions in multiple directions are difficult to handle in spectral codes (Canuto, et al., 1988) and the global nature of spectral methods make them fundamentally incompatible with patched adaptive mesh refinement (PAMR) which we intend to use in the long-term development of the code.

Initially, we planned a simulation that coupled the air and water in a single solution domain. However, in the course of code development we decided to concentrate on producing a free surface code which could be applied separately to the air and water with the interface acting as the communication channel between the domains. A coupled solution can then be obtained through an iterative method. The advantage of this technique is that it is accomplished through domain decomposition that can eventually lead to separating the solution domain into four regions: air only, water only, and two regions bounding the interface in which the effects of wave breaking, air bubble entrainment and water spray are confined. At this point we have not worked out the best iterative method for coupling the air-water simulation domains.

Patched adaptive mesh refinement (PAMR) will be important in the long run to obtain an efficient code that can respond to requirements for greater resolution in areas with large gradients. The methods for PAMR have been developed but are not yet implemented in the code.

Our modified code is a 3D, unsteady flow, large-eddy simulation (LES) that has its roots in the non-staggered grid method of Zang, et al (1994), who used a fractional step/approximate factorization method based on Kim and Moin (1985). The first step in code development was to get Zang's method to work with a moving grid (without a free surface) with 2nd order accuracy as the grid and time step are refined. The primary test cases for this were 2D flow in a lid-driven square cavity and a 2D decaying vortex. We have (1) validated the ability of the numerical code to handle a moving grid with 2nd order accuracy, (2) incorporated the grid generation code from the EAGLE grid-generation package (Thompson, 1991), (3) developed code for free-surface advancement and boundary conditions, and (4) validated code operation on the lid-driven square cavity, the decaying vortex, and two-dimensional free-surface real-fluid motion in a rectangular basin [i.e., wave sloshing]. The code is written for three-dimensional motions, but we have not ported the code to a machine large/fast enough to test these features as of this date.

Thus, the groundwork for the code is completed, and our next tasks can be divided into two areas: (1) code development, and (2) numerical experiments.

Code development

Our first task is to implement inflow and outflow boundary conditions for simulating a laboratory flume with a mechanical wave-maker. For the inlet, we are considering including the moving wave-maker as part of the boundary with velocity profiles beneath the wave-maker matching those obtained from physical experiments. For the outlet, we would prefer to use supercritical outflow from the flume as a boundary condition, however this is likely to require a larger simulation domain than would be practical. We will investigate the use of wave-absorbing boundary conditions and/or the use of a secondary dissipating domain that prevents waves from being reflected back into the primary computational domain.

A second task is to implement a subgrid-scale turbulence model to permit large-eddy simulations. We plan to use the dynamic mixed model of Zang, et al. (1993). Other numerical code-development tasks include domain decomposition, adaptive gridding and parallelization of the code.

The only fundamental piece of the physics of a material free surface that has been left out of the simulation at this point is the effect of surface tension. We will begin to attack this problem by implementing a constant surface tension coefficient in the dynamic boundary condition. Keeping in mind the premise of our long-term objective (that the code should be expandable) we will implement the dynamic boundary condition with the surface tension coefficient carried as a function of position. However, the algorithms for the transport of scalar contaminants that determine the surface tension coefficient will be left for research in the final years of this project. In this way, future research will not have to modify the dynamic boundary condition algorithm, but will only have to add algorithms which transport the scalars as a function of the velocity field and compute the surface tension coefficient as a function of the density of scalar contaminants.

The other area of code development that we intend to pursue in the near term is devising a scheme to couple air, water, and interface domains into a workable code. For the free-surface flow, we have implemented the idea of considering the surface to be an independent 2D domain (with surface-fitted curvilinear coordinates) over which the boundary conditions are solved [Hodges, et al., 1994]. Interaction between the 3D air and water domains and the 2D surface domain forms the coupled air/water solution. The computational power to run a large, fully-coupled simulation may not immediately be available, but will probably be available in the final years of this project when multiphase effects and breaking waves are considered. With the coupled simulation completed, the implementation of multiphase effects and breaking waves can be concentrated on modeling the physics in the domain immediately surrounding the interface, without concern for the decomposed domains which contain solutions for only air or only water.

Simulations

We plan to conduct two basic types of simulations:

1) Simulation of the flow beneath mechanically generated waves with an imposed current in a laboratory flume. To conduct these simulations we plan to develop inflow and outflow boundary conditions that match laboratory experiments.

2) Simulation of vortex/wave interaction produced by a surface-piercing body [a flat plate; see below] in a laboratory flume with mechanical generated waves and an imposed current.

3. PHYSICAL EXPERIMENTS

The principal goal of our laboratory work is to understand the interactions that take place between surface gravity waves and sheared turbulent flows. These interactions might include the formation of transient, intense longitudinal vortices or other large- scale coherent structures, enhancement of rates of turbulence dissipation, substantial modifications of near surface turbulence fields, and spatial redistribution of mean momentum in the flow field. Towards this end we are working to develop accurate maps of flow fields under waves with and without a surface-piercing body.

During the course of the present grant our efforts have largely been focused on two aspects of using DPIV (Digital Particle Image Velocimetry) to measure flow fields under waves: (1) automation and speeding up of the process of converting particle images into vector velocity fields (2) making measurements that are sufficiently accurate to enable us to have confidence in computed turbulence statistics and in the results of spatial differentiation like that involved in producing vorticity fields. Originally our interest in speeding up the DPIV processing was with a view towards producing 3D flow fields; however, for reasons discussed later, we have shifted our near term work to 2D DPIV where speed is still important given that thousands of velocity fields will be required to develop good turbulence statistics.

In working towards making accurate 2D DPIV measurements, we have spent a significant amount of effort on determining what 'system' parameters, e.g. camera resolution (pixel depth), particle seeding density, etc. are important to making accurate velocity measurements using the correlation technique described by Willert and Gharib (1991). In this task, we have largely used synthetic images, either randomly computer generated or by imaging sets of particles moved through carefully controlled translations. As a result of this analysis, we have concluded that our existing system does not have sufficient time resolution/accuracy or pixel depth to accurately obtain meaningful turbulence information in wavy flows.

One significant improvement we have made on the standard correlation-based DPIV technique is to use the correlation technique as a seed for particle tracking. In our method, we first calculate coarse velocity field with (typically) 32 by 32 pixel windows. We next use this velocity field to identify particle pairs for which individual displacements, and hence velocities can then be determined.

Given that each window typically contains at least 10 particle pairs, this increases the number of valid vectors per image pair by approximately an order of magnitude. With this technique, typical velocity fields contain approximately 2,000 to 4,000 vectors. Post processing includes interpolation of the measured velocities onto a regular grid using several different schemes.

As a consequence of our DPIV evaluation work, we assembled a new system based on a relatively sophisticated 12 bit, slow-scan CCD camera interfaced directly to an array-processor equipped PC clone[1]. When operating, we typically take 1 image pair every 15 seconds; of this time, 4 seconds is occupied with reading the image from the camera, the rest is associated with writing the images to disk and with other overhead in the data acquisition machine. Although this is much slower than the rate at which the flow evolves, image acquisition can be tied to the phase signal of the wave, allowing us to assemble a phase-dependent picture of waves and turbulence in the flow. Moreover, having 12 bit accuracy enables us to continue to use our 5 watt Ar-Ion laser as a light source rather than being forced to look for funds to acquire a double-pulsed Nd-YAG laser. With this system we can now measure 2D flow fields in streamwise or spanwise planes at scales ranging from the wave-scale down to the dissipation scale at accuracies of ±1% or better.

Concurrently with the DPIV work, we have completed a fairly detailed study of wave-turbulence mean flow interactions in our 1.2 m wide wave flume. The results of this effort are given in Nepf (1992). The major outcome of this work is that there is a fundamental change in flow character as the wave forcing is increased. Because of the design of the wavemaker, for sufficiently large amplitude waves (for a given frequency), the waves break near the wavemaker, leading to the development of intense streamwise vortices, and to increased dissipation and mixing in the flow. While this work is mainly being continued with support from the MBL ARI, it also has provided necessary background information for other experiments in the flume as well as data for model comparison.

The new 2D DPIV system is operational and detailed measurements in the turbulent boundary layers in an open channel in the presence of waves are underway as of this date. We are currently preparing for publication a paper describing our hybrid DPIV technique.

Our next work will involve experiments with waves propagating on turbulent flows with and without a surface-piercing object. In the first case we will look (again) at the generic flow associated with waves propagating on a turbulent flow. To some extent the purpose of this experiment is to develop a "control" case with which to compare results from the second experiment in which we will look at the effects of the waves on the boundary layer and wake associated with a flat plate inserted into the flow and extending to the bottom of the channel. This is not a trivial case for any of the present generation of free-surface codes. Accordingly, it should provide most useful data for future development and testing of free- surface codes.

The experiments have three main goals:

(1) To provide detailed information about the near surface (between trough and crest) zone where traditional measurement techniques like LDA don't work. Of particular interest are quantifying the effect of the waves on turbulence near the free-surface and in examining the dynamics of the near-surface viscous boundary layer (Longuet-Higgins, 1960) that forms adjacent to the water surface. This will involve mapping the flow in vertical and horizontal planes. For this work the comparison of turbulence modification in the nearly 2D flow we should observe in the absence of the immersed flat plate with the highly 3D field observed with the immersed plate present should be quite useful in identifying generic features of wave-turbulence interaction.

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[1]Supported by an ONR grant through the MBL ARI to Monismith, Street and Koseff (monitor: G. Geernaert).

(2) Measure spatial gradients for vorticity and dissipation in the flow. These are the things that describe the deviation of the flow from ideal/irrotational wave-like behavior, and may provide the means by which interactions between the nearly irrotational waves and the strongly rotational turbulence are accomplished. Moreover, the vertical vorticity of the mean flow over the immersed plate might be expected to lead to strong streamwise vortices as seen by Nepf and Monismith (1991) for wavy channel flow in a narrow flume. These vortices could substantially modify the mean and turbulent flow structures of the wake behind the plate. Vorticity and dissipation measurements will be key to quantifying this change in flow behavior.

(3) Provide high-quality 2D flow field data to use to test our free-surface code. The DPIV technique we have been developing is sufficiently flexible that we should be able to provide, albeit using different sampling strategies, highly resolved 2D velocity and vorticity fields that either cover the entire flow depth for 1 or 2 wavelengths or resolve regions of the order of 2 cm on a side at any point in the water column, including regions near the free surface.

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Zang, Y., R.L. Street, and J.R. Koseff, "A non-staggered grid, fractional step method for time-dependent incompressible Navier-Stokes equations in general curvilinear coordinate systems," *J. Comp. Physics*, in press, expected August 1994.

Zang, Y., R.L. Street, and J.R. Koseff, "A dynamic mixed subgrid-scale model and its application to turbulent recirculating flows," *Physics of Fluids A*, Vol. 5, Part 12, pp. 3186-3196, 1993.

Appendix 2. Dissertations

[Available from University Microfilms, Ann Arbor, MI]

J. A. Harris, "On the growth of water waves and the motions beneath them," Department of Civil Engineering Ph. D. Dissertation, Stanford University, March 1992, 341 pages [work supported sequentially by ONR Grants N00014-84-K-0242, N00014-90-J-1294, and N-00014-J-91-1200].

Nepf, H.M., "The production and mixing effects of Langmuir circulations," Department of Civil Engineering Ph. D. Dissertation, Stanford University, August 1992, 134 pages.[work jointly supported by this grant, ONR Grant N-00014-91-J-1200, and NSF Grants CTS 8958314 and OCE 8919230, and a gift to Stephen G. Monismith from the Charles Lee Powell Foundation]

Yan Zang, "On the development of tools for the simulation of geophysical flows," Department of Mechanical Engineering Ph. D. Dissertation, Stanford University, June 1993, 224 pages [work jointly supported by this grant, ONR Grant N-00014-91-J-1200, and NSF Grant CTS-8719509].

Appendix 3. Publications

Harris, J. A., and R. L. Street, "Numerical simulation of turbulent flow over a moving wavy boundary: Norris and Reynolds extended," *Physics of Fluids A*, Vol. 6, Part 2, pp. 924-942.

Nepf, H.M., and S.G. Monismith, "Experimental study of wave-induced longitudinal vortices," *J. Hydraulic Engineering*, vol. 117, Part 12, pp. 1639-1649, 1991.

Zang, Y., R.L. Street, and J.R. Koseff, "A dynamic mixed subgrid-scale model and its application to turbulent recirculating flows," *Physics of Fluids A*, Vol. 5, Part 12, pp. 3186-3196.

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